FINITE ELEMENT MODELING OF THE INTERFACIAL BEHAVIOR AT SURFACE ROUGHNESS CONCRETE WITHOUT THE PROJECTING STEEL

[1]MAZIZAH EZDIANI MOHAMAD, [2]IZNI SYAHRIZAL IBRAHIM, [3]REDZUAN ABDULLAH

[1]Department of Civil Engineering, School of Engineering & Technology, University College of Technology Sarawak, Sibu, Sarawak, Malaysia
[2,3]Department of Structural and Material, Faculty of Civil Engineering, Universiti Teknologi Malaysia, Malaysia
E-mail: [1]mazizah@ucts.edu.my, [2]iznisyahrizal@utm.my, [3]redzuan@utm.my

Abstract- The development of composite action between precast concrete slab and concrete toppings is important to provide a monolithic behavior of composite concrete. The current Eurocode 2 provides design expression for interface shear strength of both concrete base and concrete topping. In this paper, the finite element modeling is presented and calibrated with experimental results. The interface shear strength between precast concrete slab and cast-in place concrete topping slabs was evaluated through a set of 9 push-off experiments. Finite Element Modeling package ABAQUS 6.12 was used to model the interface bond of concrete-to-concrete layers. The push-off test specimens featured segments of precast concrete slabs sized 300 mm × 300 mm × 100 mm with a variety of surface textures including trowel finished, indented and wire-brush roughened. A cast-in place concrete was poured on top of the concrete base to form a 300 mm × 300 mm × 75 m concrete topping. Failure of the bonded interfaces was modeled with cohesive zone model (CZM) approach with zero thickess interface element. The parameters used in the analysis include interface shear strength, fracture energy and elastic shear stiffness. The study shows that the difference between the model and experimental results is relatively small and therefore shows the capability of the finite element modeling to carry out interface analysis.

Keywords- Surface Textures, Interface Shear Strength, and Finite Element Modeling.

I. INTRODUCTION

In order for the composite slab to behave in a monolithic behavior, the composite interface bond must remain intact and the interface shear stress must be transferred efficiently along the interface [1]–[3]. Composite concrete slab construction is where the combination of precast concrete slab and cast-in place concrete topping are designed to provide stability and efficient system as a single element. Without adequate interface shear transfer, the flexural and shearing capacities of the slab diminished. Therefore, it is essential to achieve the optimum shear strength between the concrete layers to ensure composite action of the two members.

Design equations of the interface shear strength in both Eurocode 2[4] and CEB-FIB Model Code 2010[5] considered the following parameters: concrete tensile strength, friction coefficient, concrete cohesion, steel reinforcement and normal stress at the interface. However, very little information on the characterization of the roughness of interface which is in the most codes of practice still remains qualitative[6]–[8]. CEB-FIB Model Code 2010[5]stated the average roughness, R_a as the roughness parameter to quantify the strength of concrete-to-concrete bond, while Eurocode 2[4] is based on qualitative assessment. Previous researchers[6][9] proved that friction coefficient and concrete cohesion can be quantified by the roughness parameter. Santos et. al.[10]modeled a 2-dimensional specimen with steel crossing the interface and identified each of the following parameters: elastic shear stiffness, internal friction angle, dilatancy angle, cohesion fracture energy and bond slip relation between steel and concrete.

Several researchers[10]–[13]havesuccessfully applied the adhesively-bonded repair, concrete-to-concrete and adhesive (FRP and CFRP)-to-concrete techniques for Civil Engineering applications. They used CZM to define the fracture of concrete and other quasi-brittle materials. Furthermore, Hadjazi et al. [14] concluded that the interface crack model can represent bond behavior. Wang[15] established a bond-slip model to study the interface debonding for FRP-plated reinforced concrete (RC) beam induced by flexural crack.

In this paper, a comprehensive identification on the composite concrete without steel reinforcement crossing the interface is aimed: interface shear strength, elastic shear stiffness and fracture energy. The study utilized a 3-dimensional finite element method to analyze composite concrete subjected to the push-off shear test to obtain the horizontal load-interface slip relationship. The modeling of concrete-to-concrete bond used Cohesive Zone Modeling (CZM) approach with zero thickness element. The interface shear bond characteristic of the composite concrete model was deduced from push-off test data. The models are determined for the following three parameters: (i) interface shear strength, (ii) elastic shear stiffness and (iii) fracture energy.

II. COMPUTATIONAL MODEL

2.1. Finite Element

As in the experimental "push-off" test shown in Figure 1, concrete base with concrete topping is modeled in 3-Dimensional (3D) as shown in Figure 2. The dimension of the specimen is 300 × 300 × 100 mm for the concrete base and 300 × 300 × 75 mm for the concrete topping, which gives a total shear plane area of 90000 mm^2. The 3D stress model is chosen because it could give an accurate representation of the specimen in the experimental work by including the parameters of the interface shear failure. The model is analyzed using displacement control for better simulation with the experimental results.

Figure 1 "Push-off" test setup

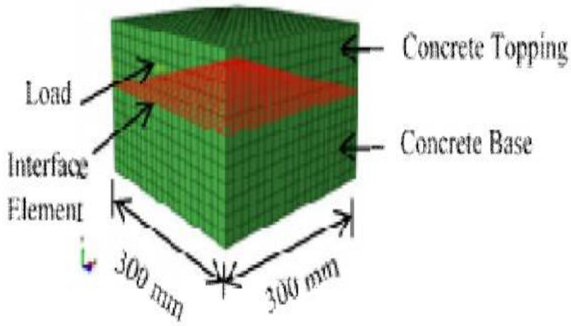
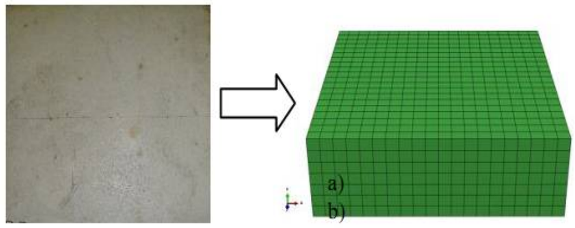


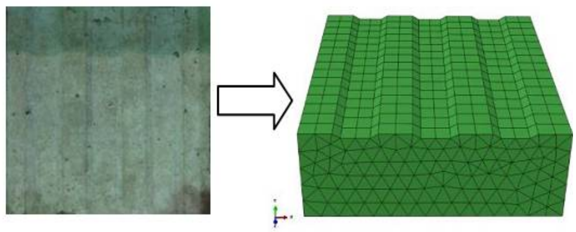
Figure 2"Push-off" FE model

Three (3) types of surface textures are modeled which includes trowel finished, indented, and wire-brushed roughened as shown in Figure 3.The Modulus of Elasticity for both concrete base and concrete topping are assumed according to Eurocode 2 [4]. FE modeling properties for interface is shown in Table 1. The trowel finished is modeled with 3-dimensional solid element of an 8-node linear brick (hexahedral), reduced integration and hourglass control, C3D8R and the indented and wire-brush roughened are modeled with a 6-node linear triangular prism, C3D6.

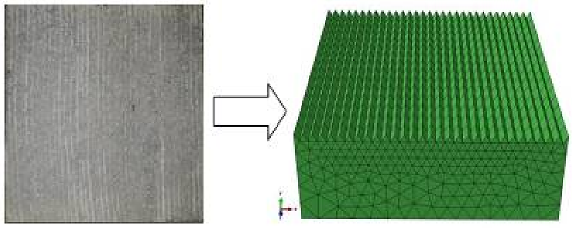
The interface concrete is modeled as interface element to connect the two surfaces of the concrete layers. The interface element is a zero-thickness embedded in the model via shared nodes or tie constraints to connect the concrete base and concrete topping [10][16]–[19]. The 3-dimensional interface element is used in the analysis which is COH3D8.



(a) Trowel finished



(b) Indented



(c) Wire-brush roughened

Figure 3Surface Textures: (a) Trowel finished, (b) Indented, and (c) Wire-brush roughened

Table 1: FE modeling properties for interface

Item	Assumption
Mode of analysis	ABAQUS/Standard
Surface element type (trowel finished surface)	Hexahedral C3D8R (Continuum 8 node linear brick, reduced integration, hourglass control)
Specimen element type (indented and wire-brush roughened surfaces)	C3D6 (Continuum 6 node linear triangular prism)
Interface element	COH3D8
Constitutive model	Cohesive Zone Model (CZM)
Modeling steps	3 steps +1 initial

2.2 Material Behavior

Table 2 shows the concrete properties used for the concrete base and concrete topping, while the steel properties for the projecting steel is shown in Table 3. The average stress-strain curve from theoretical of Wang and Hsu[20] steel model for the 6 mm diameter mild steel bar embedded in concrete is shown in Figure 4.

Table 2 Concrete properties

Concrete Properties	Value
Elastic Modulus	35 GPa (Concrete Base) 30GPa (Concrete Topping)
Poisson ratio	0.20 (Concrete Topping) 0.17 (Concrete Base)

Table 4 Steel R6 properties

Steel Properties	Value
Elastic Modulus	209 GPa
Yield stress	250 MPa

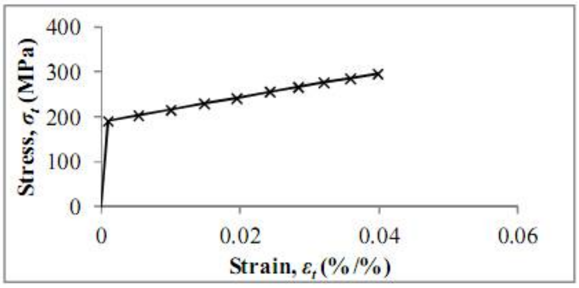


Figure 4 Theoretical tensile stress-strain relationships for 6 mm diameter mild steel bar using Wang and Hsu [20] model

2.3 Interface Element Behavior

Interface element plays an important role to predict the interface shear strength of concrete-to-concrete bond. The interface element is modeledwith interface failure behavior using the traction-separation approach which is Cohesive Zone Modeling (CZM). The approach is represented as linear pressure dependent where the interface element is modeled with continuum approach.

2.4 Cohesive Zone Modeling (CZM)

The CZM includes a constitutive relation between the traction, τ acting on the interface and the corresponding interface separation, δ (displacement or slip at the interface). Traction separation law is applied as shown in Figure 5 where it is typically characterized by the interface shear strength, N and fracture energy, G_{TC}. The area under the traction-separation curve shows the fracture energy, G_{TC}. Linear elasticity with damage analysis is available in both ABAQUS/Standard. Modeling of damage analysis under the general framework is a) damage initiation, b) damage evolution, and c) removal of elements. From the experimental results, the critical fracture energy can be extracted using the following expression:

$$G_{TC} = \frac{1}{2} \times N \times \delta \times 1000 \qquad (1)$$

where N is the load (N) and δ the displacement (mm).

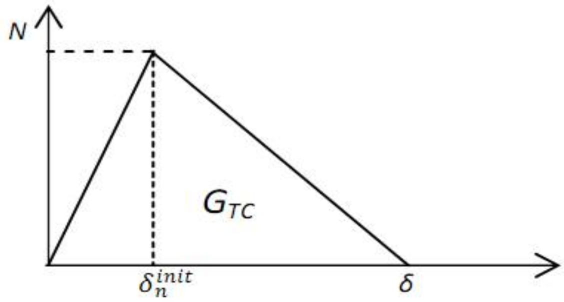


Figure 5 Typical traction-separation approaches

Since the interface element is zero-thickness, the cohesive section properties thickness, $h_{eff}$is taken as 1. The Elastic Modulus of the traction separation law is interpreted as penalty stiffness. The stiffness that relates interface shear strength to displacement is given as:

$$K_n = N_{max} / \delta_n^{init} \qquad (2)$$

where N_{max} is the peak load and δ_n^{init} is initial interface slip

2.1. Finite Element Mesh

The first stge of the model development was to carry out the sensitivity analysis for each surface texture. Three simplified finite element meshes for monolithic plain concrete are first analyzed: coarse mesh, medium coarse mesh and refined mesh, with average element sizes of 20 mm, 15 mm and 5 mm. Figures 6, 7and8 show the finite element meshes of specimens with surface textures of trowel finished, indented, andwire-brush roughened, respectively. The relationships and graph patterns are almost the same between the different element sizes for trowel finished and indented surfaces with a maximum difference of 2.23% of the peak shear load. Meanwhile, the wire-brush roughened surface shows similar graph pattern for element size of 15 mm and 20 mm with 3.31% differences of the peak shear load and comparison between size of 5 mm and 20 mm show the percentage peak shear load differences of only 0.45%. However, the interface slip at peak shear load for element size of 5 mm is 6.76 mm, compared to that of 8.11 mm and 8.44 mm for element size of 15 mm and 20 mm, respectively. The analyzed data reveals that small differences are only found around the tip of the interface, where rapid geometry change occurs. The percentage differences of the peak shear load in the sensitivity analysis among the element sizes are less than 20%, therefore the coarse mesh of element size 20 mm are selected to perform the parametric study in the small-scale modeling.

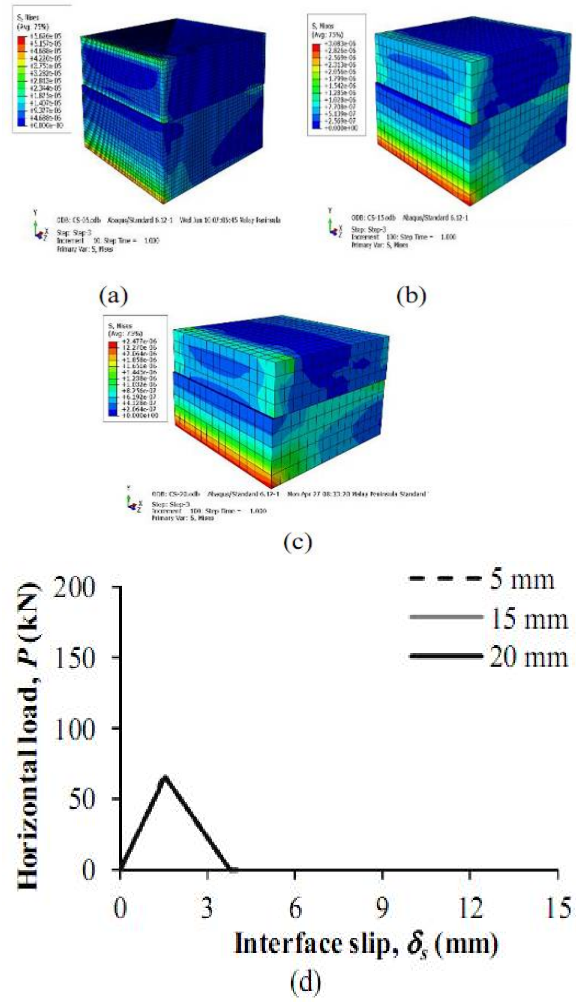
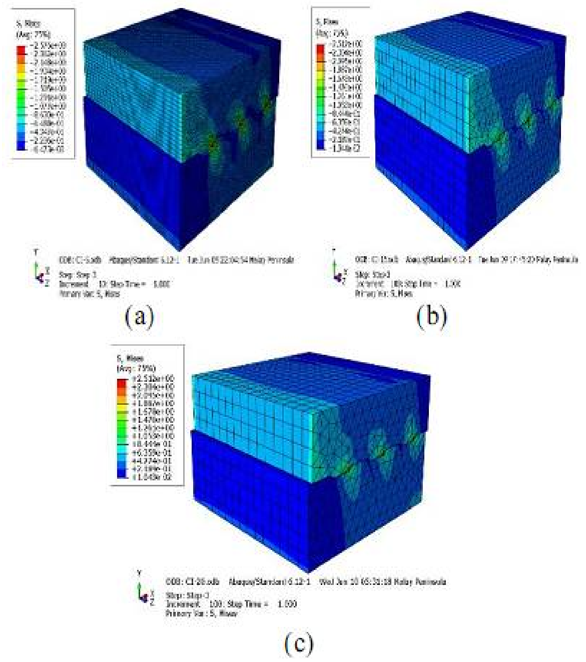


Figure 6 Sensitivity analysis using meshing sizes for smooth or left “as-cast” surface: (a) refined mesh (5 mm), (b) medium coarse mesh (15 mm), (c) coarse mesh (20 mm), and (d) horizontal load-interface slip relationships



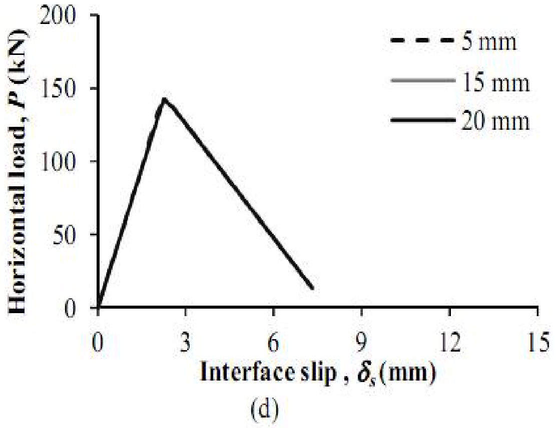


Figure 7 Sensitivity analysis using meshing sizes for indented surface: (a) refined mesh (5 mm), (b) medium coarse mesh (15 mm), (c) coarse mesh (20 mm), and (d) horizontal load-interface slip relationships

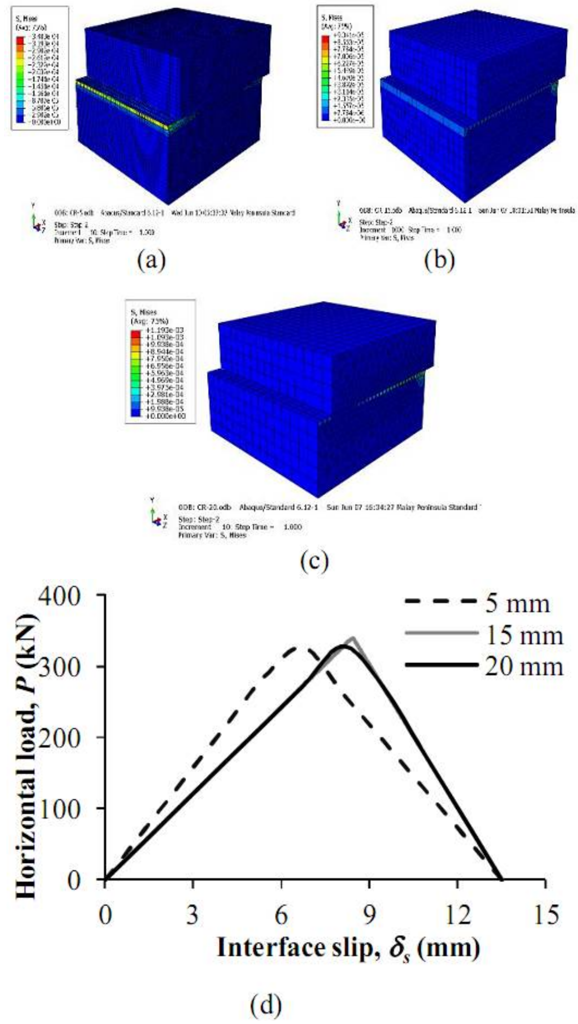


Figure 8 Sensitivity analysis using meshing sizes for transverse roughened surface: (a) refined mesh (5 mm), (b) medium coarse mesh (15 mm), (c) coarse mesh (20 mm), and (d) horizontal load-interface slip relationships

III. RESULTS AND DISCUSSION

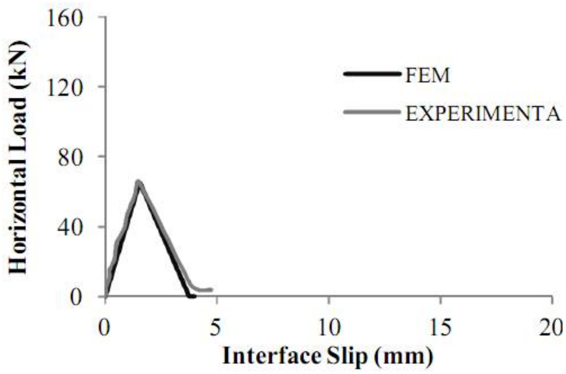
3.1. Horizontal load-interface slip

To evaluate the influence of interface shear strength and stiffness on the interface shear failure for different surface textures, three sets of interface shear-slip curves from experimental test were examined. The variations on the surface geometry depend on the surface textures at the interface.

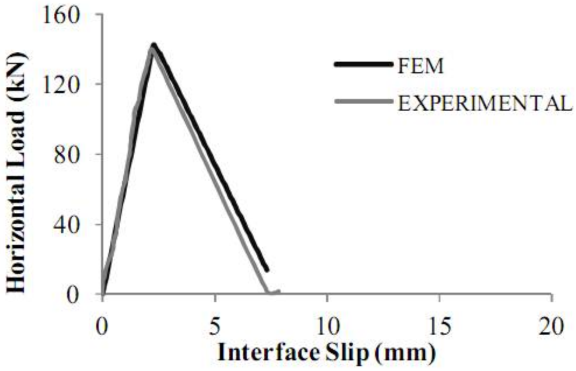
In Figure 9the horizontal load-interface slip graphs include the results of FEM and experimental for all surface textures. The differences between the FEM and experimental results are relatively small for each surface texture, where: (a) trowel finished at 0.01%, (b) indented at 2.00%, and (c)wire-brush roughened at 0.04%.

The mechanism to break the concrete interface bond between precast concrete slab and cast-in-place concrete can be modeled by using CZM approach. The separation of concrete layers occurs after attaining the peak load. The trowel finished, indented and wire-brush roughened surfaces show the traction-separation behavior at the interface. The CZM approach is suitable for modeling the brittle behavior, which is the same case for the concrete-to-concrete bond without the projecting steel. The crack initiation point occurs at ultimate horizontal load before the sudden failure at interface which breaks apart the concrete layers.

The interface shear strength increased as the degree of roughness increased. The wire-brush roughened surface is the highest degree of roughness surface texture that contributing to the highest interface shear strength compared to indented and trowel finished surfaces.The adopted FE models have provided a good agreement with the experimental results, adequately simulating and explaining the behavior of the push-off tests. In addition, it is emphasized that the role of each parameters were identified properly during the test on the overall composite concrete response.



(a)



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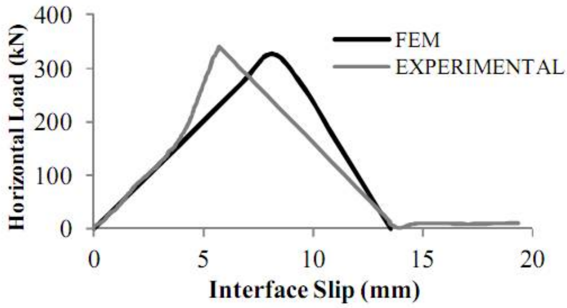

(c)

Figure 9 Horizontal load-interface slip relationships: (a) trowel finished surface, (b) indented surface, (c) wire-brush roughened surface

CONCLUSIONS

FE package using ABAQUS/Standard was used to model and analyze analytically the interface shear strength by adopting the "push-off" test method as in the experimental test. The behavior of precast concrete slab and cast-in-place strengthened is strongly influenced by the behavior of the concrete-to-concrete interface. This paper aims at contributing to a better understanding of the interface properties of the following:interface shear strength, fracture energy, elastic shear stiffness and horizontal load-interface slip relationship between concrete-to-concrete bond using analytical modeling. The findings from the study can be concluded as follows:

1. The concrete-to-concrete bond is modeled using the CZM approach at the interface concrete without the projecting steel.
2. The results of the FE model and experimental results meet an agreement with less percentage differences.
3. The model and analysis procedure can be used to predict the behavior of composite concrete layer cast at different times.
4. Interface shear strength and fracture energy control the attained peak load.

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